Series Compensated Line Protection: Practical Solutions

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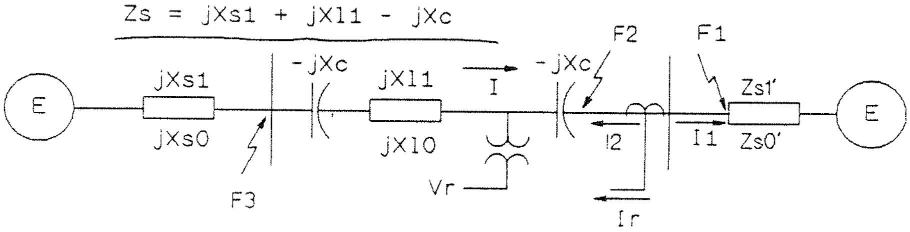
A paper entitled "Series Compensated Line Protection: A practical Evaluation"(1) was presented to this conference in 1989. Problems associated with the protection of lines with series capacitors were discussed, but no specific solutions were given. Practical solutions to some of these problems are herein presented. The techniques discussed are used in various GE equipments(2)(3)(4)(5) which are applied at various locations throughout the world.

Dynamic Response

Distance functions are designed to perform correctly on a resistive/inductive system. When series capacitors are introduced to the power system, the normal voltage/current relationships can be affected when fault levels are not sufficient to produce flashing of the gaps or to produce significant conduction in the MOV's used to protect the capacitors.

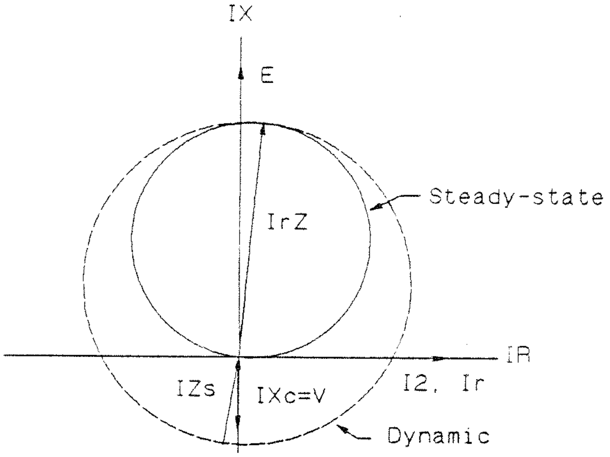


Simple System With Series Compensation

Figure 1

Consider the three-phase faults shown at F1 and F2 in Figure 1. The voltage at the right terminal of the line will be reversed from normal if gap flashing/MOV conduction does not occur, and distance functions located there will respond differently for each fault because F2 is an internal fault, whereas F1 is external to the line. Distance functions, when properly set, can be used under these circumstances, but the dynamic response must be relied on if correct performance is to be obtained.

The response of a distance function for the internal fault at F2 is shown in Figure 2. Note that the plot is made on and IR-IX basis which can be viewed as an equivalent R-X diagram if the current (I) is ignored. The diagram shows that a distance function looking in the forward direction (to the left in Figure 1) will operate correctly on a dynamic basis because the fault impedance, Xc, plots within the dynamic characteristic. But, it will not operate steady-state because Xc plots outside of (behind) the characteristic for this condition. Please note that the characteristic shown in Figure 2 applies for faults in the forward direction only. The function is directional; the area shown below the IR axis applies only for capacitive faults in the forward direction and NOT for faults behind it.



NOTE: area below IR axis applies for forward directioncapacitive faults only, not for reverse faults.

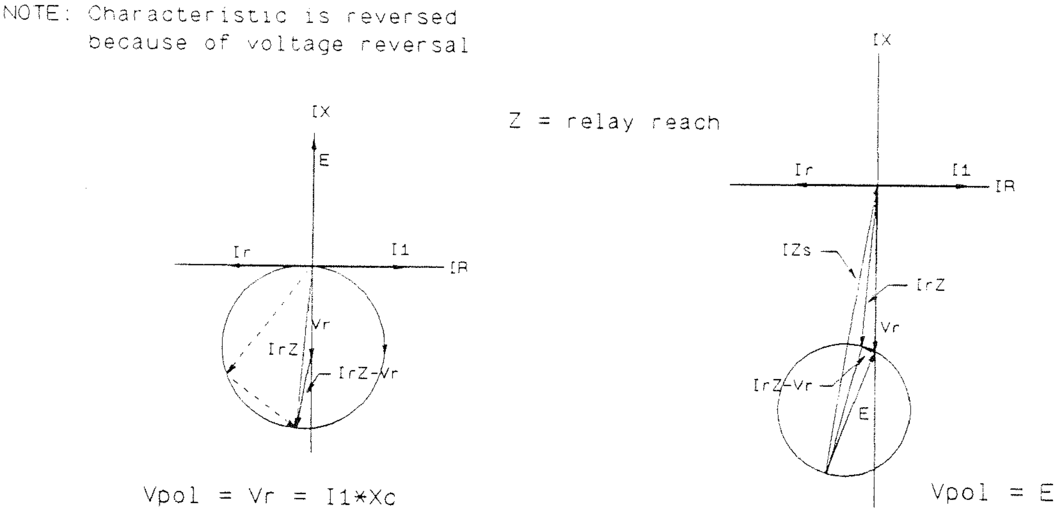
Response of Mho Function for Fault at F2 in Figure 1

Figure 2

The characteristic of the same distance function for the external reverse direction fault at F1 is shown in Figure 3. Whether the function will operate on a steady-state or dynamic basis will depend on the reach of the function relative to the capacitive reactance, Xc.

a. If the reach is less than Xc, the function will operate dynamically (Figure 3b) but will not operate steady-state. This is of concern when trying to set a zone 1 function so that it will not overreach for a fault beyond a series capacitor at the remote end of the line (F3 in Figure 1). For example, consider a a zone 1 function that is applied at the right end of the line shown in Figure 1. If the reach setting required to prevent operation for faults at F3 must be made less than the reactance of the capacitor located behind it, then the function will operate dynamically for faults at F1. Thus, in these applications and for other reasons to be discussed below, it may not be possible to apply a pure zone 1 direct tripping distance function.

b. If the reach is greater than Xc, the function will operate steady-state (Figure 3a), but not dynamically. Since the overreaching functions in most pilot relaying schemes have a reach setting greater than Xc, they will not operate dynamically. In a properly designed relaying scheme, this will allow sufficient time to establish that the fault is external to the protected line and so prevent tripping in the event the fault hasn't been cleared before the overreaching functions operate steady-state. Such a scheme requires the use of blocking functions as shown in the simplified logic of Figure 4. The blocking functions are set to look away from the protected line, and will operate dynamically for external faults. The dropout time (B) of the characteristic timer for the blocking function is set relatively long to prevent the


NOTE: Characteristic is reversed because of voltage reversal

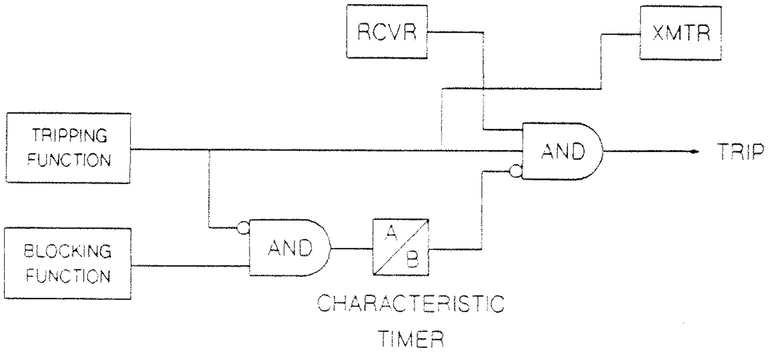
a. Steady-state Characteristic

b. Dynamic Characteristic

Response of Mho Distance Function for Three-phase Fault at F1 in Figure 1

Figure 3

tripping function from initiating a trip before the external fault is cleared by the protective relays located on that line. Note that the tripping functions will operate dynamically for all internal faults (see Figure 2). They will operate faster than the blocking functions and will prevent them from operating by applying the NOT input to the AND shown in Figure 4.

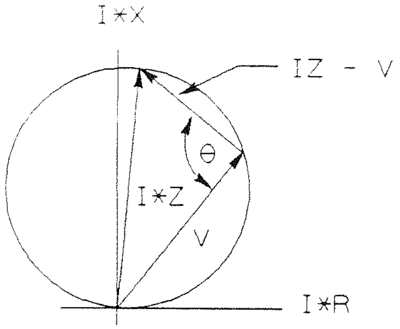


Simplified Scheme Logic

Figure 4

Zone 1 Direct Tripping Functions

A simple zone 1 function can be derived as shown in Figure 5. In this function, operation occurs whenever the angle θ between the operating quantity (I*Z - V) and the polarizing quantity V is less than 90 degrees.



Z = Relay Reach
I = relay current
V = relay voltage and polarizing quantity
I*Z - V = relay operating quantity

Simple Mho Distance Function

Figure 5

Consider that such a function is applied at the location illustrated in Figure 1. On the surface, it appears that the function could be set to reach 80-90 percent of the compensated impedance of the line ($Xl1-Xc$) to provide direct tripping. However, it was shown in the earlier paper that the function may overreach on the low frequency transients that could occur for faults beyond the capacitor when the fault level is insufficient to cause flashing of the gaps or to produce significant conduction in the MOV's used to protect the capacitors. It was also shown in that paper that it may not be possible to set this function with a short enough reach to prevent overreaching. Secondly, if a short enough reach could be found, it was just shown above that the function could operate for faults beyond capacitors located behind it. It was for this reason that a combined overcurrent/distance function was developed. In the simple distance function, the measurement is made by comparing the phase relationship of the operate signal ($IZ-V$) to the polarizing signal Vp; where Z is the reach of the function, and, V and I are the voltage and current at the function. In the combined distance/overcurrent function, the operate signal must also be larger than a user set magnitude in addition to having the correct relationship to the polarizing quantity. The level detector setting is determined by the amount of compensation and type of protection used around the compensation.

For example consider the fault at F3 in the system shown in Figure 1. For this fault, the voltage at the relay is:

$$Vr = Ir*(Xl1 - Xt)$$

Where,

Xt = Xc when gaps are used and are not flashed, or,
= zero when gaps are flashed

Xt = parallel combination of Xc and the MOV's when the latter are conducting, or, is equal to Xc when the MOV's are not conducting

If the zone 1 function is set with a reach, Z, equal to $Xl1$, then the operate signal ($IrZ-Vr$) for the fault at F is:

$$IrZ - Vr = Ir*(Xl1) - Ir*(Xl1-Xt) = Ir*Xl1 - Ir*Xl1 + Ir*Xt$$

$$= Ir*Xt$$

If gap flashing does not occur, of if there is not significant conduction in the MOV, then the operate signal, $IrZ-Vr$, is equal to $Ir*Xc$, the voltage across the capacitor. The level detector in the zone 1 function is set larger than this value so that it cannot operate for faults external to the zone of protection, even in the presence of low frequency transients.

If, for the fault at F3, the gaps flash or significant conduction occurs, then Ir*Xt is equal to zero if the gaps flash, or is less than or equal to the MOV protective level. Because this is less than the level detector setting, the function will not operate and is very secure for this condition. Similar reasoning can be applied to show that the function can be set properly so that it will not operate for reverse faults when capacitors are located between the function and the fault.

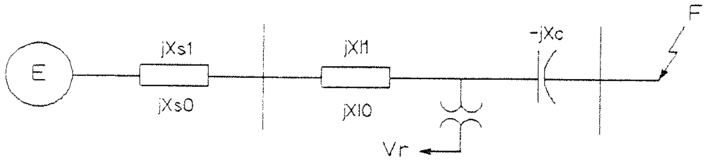
Now consider a fault directly in front of the function. For this fault (Vr = 0), and the operate signal IrZ-Vr = Ir*Z = Ir*Xl. If the source behind the function is very strong and/or the line is very long, the operate signal will be very large and fast operation will result. Both analog and EMTP model power system testing have demonstrated operating times in the 3-4 millisecond range for heavy close-in faults while maintaining a high degree of security for faults external to the line.

Polarizing Choice, Phase and Ground Distance Functions

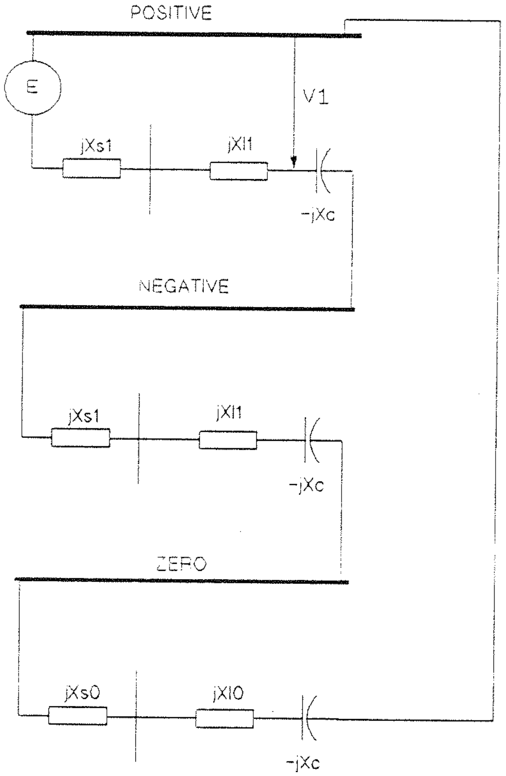
A number of choices are available in selecting the polarizing quantity to be used in phase and ground distance functions. The simple distance function described above uses the faulted phase/phase-pair voltage as the polarizing quantity. This choice has many drawbacks; including poor performance on series compensated lines, poor arc/fault resistance coverage, non-operation for zero voltage faults, and relatively poor performance in single-phase tripping schemes. Consequently, other quantities which provide better performance are commonly used. One choice is positive sequence voltage polarization which provides significant improvements in performance for the drawbacks just described.

When distance functions are applied near series capacitors, they can be made to operate properly on a dynamic basis, but, depending on the type of polarization, they may operate incorrectly on a steady-state basis as a result of the voltage reversals that can occur. Positive sequence voltage polarization will not prevent steady-state operation for three-phase faults, but will prevent it in many cases for unbalanced faults. For example, consider the simple system shown in Figure 6. In this system, the phase-to-ground voltage at a relay looking to the left will reverse for the phase-to-ground fault shown. The positive sequence voltage referenced to the faulted phase will not reverse however unless the capacitive reactance, Xc, exceeds the following value:

$$X_c > \frac{X_{s1} + X_{l1} + X_{l0} + X_{s0}}{3}$$



a. Simple System with Series Compensation



b. Network Connections for Phase-to-Ground Fault

Figure 6

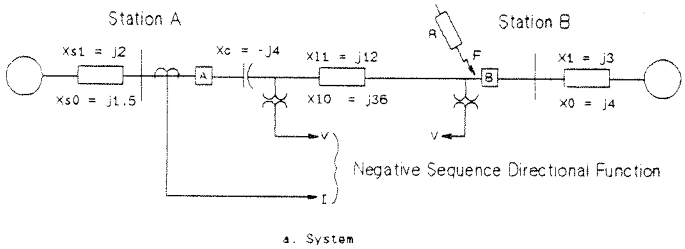
Similar analysis can be made for phase-to-phase and double-line to-ground faults to show that the functions will also perform properly on a steady-state basis for many of these faults.

Distance functions with positive sequence voltage polarization will provide continuous outputs for all but three-phase zero voltage faults because there will be some positive sequence voltage for all but three-phase faults. Dynamic performance is relied on for zero voltage three-phase faults.

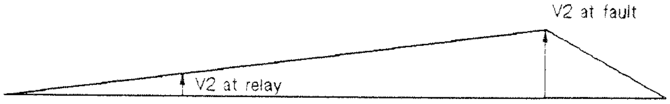
Positive sequence voltage polarization also provides increased security for faults behind the function and excellent performance in single-phase tripping schemes.

Directional Overcurrent Functions

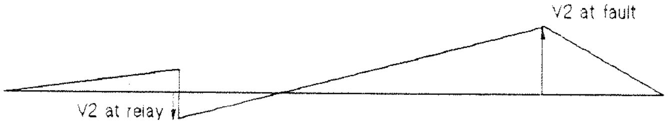
Directional overcurrent functions can be used to provide excellent protection for high resistance ground faults but are susceptible to misoperation as a result of the voltage reversals that can occur for faults near series capacitors. In addition, zero sequence



a. Typical System with Series Capacitors



b. Negative Sequence Voltage Profile (capacitor gaps flashed).



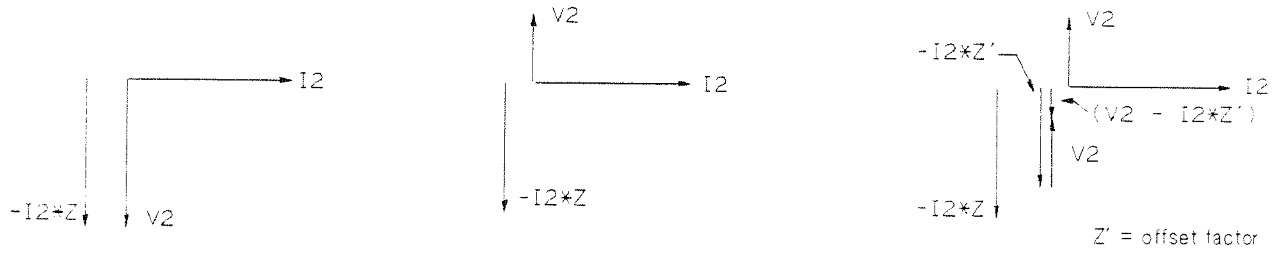
c. Negative Sequence Voltage Profile (capacitor gaps not flashed).

Figure 7

directional functions are also susceptible to the effects of mutual coupling from parallel lines.

Consider the system shown in Figure 7. For the fault shown, the negative sequence voltage at the relay will be reversed from normal when the fault current is not sufficient to cause flashing of the gaps or to produce significant conduction in the MOV's used to protect the capacitors. The zero sequence voltage can be similarly affected. If the reversed voltage is used in a directional function, the fault would appear to be external rather than internal to the line as shown in the Figure. Negative sequence directional functions are not affected to any extent by mutual coupling; and, they can be made secure from voltage reversals with the addition of an offset/compensating signal. Figure 8 shows in phasor form the performance of a simple negative sequence directional function versus the operation of a function with the offset/compensating feature. The performance of the functions are such that operation will occur whenever the I2*Z quantity is within 90 degrees of the V2 quantity in the simple function or within 90 degrees of the V2 - I2*Z'quantity in the compensated function. The offset/compensation factor must be set greater than the difference between the source impedance and the capacitive reactance shown in Figure 7;i.e., (Z' > Xs1 - Xc).

NOTE: V2 and I2 phasors are for single-line-to-ground faults shown in Figure 7



a. Uncompensated Function
V2 vs -I2*Z
Capacitors bypassed

b. Uncompensated Function
V2 vs -I2*Z
Capacitors not bypassed

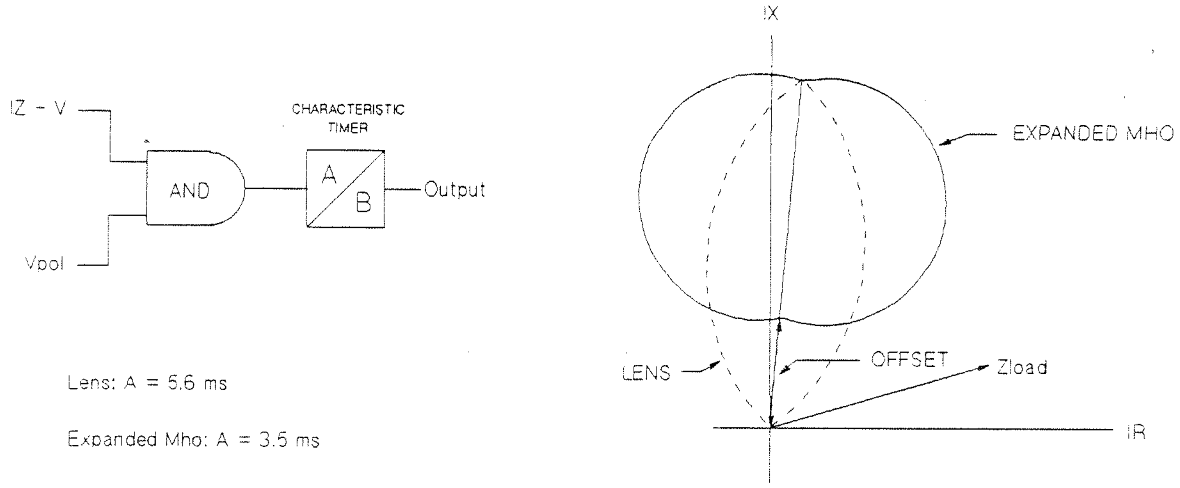
c. Compensated Function
(V2 - I2*Z') vs -I2*Z
Capacitors not bypassed

Performance of Negative Sequence Directional Functions on a Series Compensated Line

Figure 8

Forward Offset

A distance function can be made lenticular to minimize the effects of load, or forward offset can be used to achieve the same affect as shown in Figure 9. Furthermore, with the offset in, it is possible to use an expanded mho characteristic as opposed to a lenticular characteristic that would otherwise be required. This is also shown in Figure 9. Since the expanded mho characteristic is obtained by using a lower timer setting on the characteristic timer, the fastest possible operating time can be obtained for close-in heavy faults. Please note that the function will operate dynamically for forward faults in the offset area.



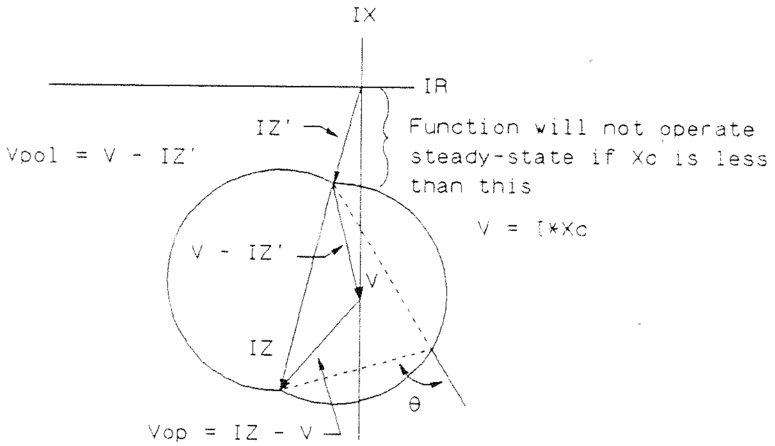
a. Simple Phase Angle Comparator

b. Characteristics

Expanded Mho with Offset versus Lens Characteristic

Figure 9

The offset will also be beneficial when the function is applied on some series compensated lines. For example, consider that a three-phase fault occurs at F1 in Figure 1. The apparent impedance, on a steady-state basis, will plot in the offset area (outside of the characteristic) if the offset is greater than the capacitive reactance of the capacitor (see Figure 10). Thus, the function will not operate steady-state, or dynamically as described earlier under dynamic response (Figure 3b). Since this is an external fault, this performance is desirable.



Function operates when angle between Vop and Vpol is less than θ degrees

Steady-state Characteristic of Offset Mho Distance Function
for three-phase Fault at F1 in Figure 1

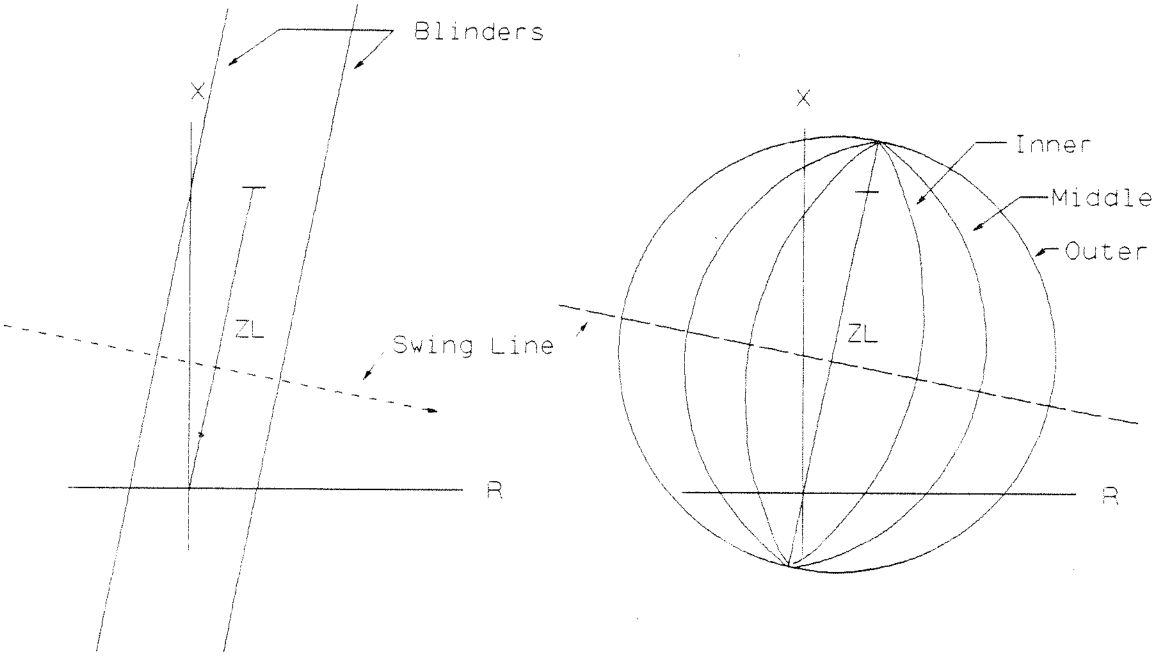
Figure 10

Asymmetrical Gap Flashing

Asymmetrical flashing of the gaps in one or two phase of the transmission line causes negative and zero sequence currents to flow in the transmission line. If either of these currents were used alone to operate an overcurrent function, then this function may operate when operation is not really called for. It is possible to minimize, and in some cases eliminate, the effects of the gap flashing by using overcurrent functions that have positive sequence current restraint. For example, a negative sequence current function would have as its operating quantity (I2 - K*I1) and a zero sequence current function would have as its operating quantity (I0 - K*I1). Either or both of these functions will still provide excellent coverage for high resistance ground faults, but with the security provided by the positive sequence current restraint.

Out-of-Step Tripping

Out-of-step tripping can be instituted in a number of ways. One method uses blinder functions as shown in Figure 11a. Positive sequence distance functions can also be used as shown in Figure 11b.



a. Blinders

b. Positive Sequence Distance Functions

Out-of-Step Tripping

Figure 11

Positive sequence distance functions have the following advantages over the blinder scheme.

1. The positive sequence distance functions have a defined reach in both the forward and reverse directions, thus making them less susceptible to operation on swings external to the protected line.

2. The swing must cross both of the characteristics in the blinder scheme before a decision to trip can be made. The swing must pass through three characteristics (outer, middle, and inner) before a trip decision can be made. Tripping can be initiated once the inner characteristic is entered, or it can be delayed until the swing leaves the outer characteristic.

3. Gap flashing and capacitor reinsertion for some SLG faults near a series compensated line can cause the fault impedance to vary greatly. In fact, it may move in a manner similar to a swing condition which could cause undesirable operation of the out-of step tripping system. Mho distance functions that measure positive sequence impedance are less susceptible to operation for this condition.

Conclusions

Series compensated lines offer unique problems to the protection engineer. These problems are not unsurmountable and relays and schemes have been developed for use in the protection of these lines. The solutions to many of these problems have been presented herein. The techniques used to implement these solutions have been available for many years and have many years of experience on relaying schemes applied throughout the world.

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